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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NUSC TD 7875	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Underwater Systems Center 6b. OFFICE SYMBOL (If applicable) 3321	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) New London Laboratory New London, CT 06320	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Naval Sea Systems Command 8b. OFFICE SYMBOL (If applicable) 63D	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20362	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 63553N PROJECT NO. D20021 TASK NO. WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
AMPLITUDE AND SPECTRAL CHARACTERISTICS OF LOW GRAZING ANGLE ACOUSTIC BACKSCATTER

12. PERSONAL AUTHOR(S)
Paul D. Koenigs

13a. TYPE OF REPORT	13b. TIME COVERED FROM ____ TO ____	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
		1987 February 17	16

16. SUPPLEMENTARY NOTATION
A Paper Presented at the 112th Meeting of the Acoustical Society of America, 8-12 December 1986, Anaheim, California

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Acoustic Shadowing	Distant Reverberation
			Azimuthal Reverberation	Doppler Shift
			Backscatter Spectra	Low Frequency Active Sonar

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Acoustic backscattering from the sea surface at grazing angles in the region of 5 degrees is affected by shadowing. Under these conditions the equations presented by Bass, Fuks, et al. (IEEE Transactions on Antennas and Propagation, vol. AP-16, no. 5, Sept. 1968) may be combined to form a single equation. The agreement between experimental data near 1 kHz and the unified equation is good. The frequency shift of the backscattered acoustic energy is dependent on wave height and period through the horizontal orbital particle velocity. The frequency spread of backscattered energy is still dependent on the same particle velocity but is diminished because the wave troughs are preferentially insonified. The experimentally determined values of backscattering strength compare favorably with other reported low frequency, low grazing angle data.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Paul D. Koenigs	22b. TELEPHONE (Include Area Code) (203) 440-4835 — 22c. OFFICE SYMBOL 3321

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

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18. (Cont'd)

Low Grazing Angle
Reverberation
Surface Backscatter

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NUSC Technical Document 7875
17 February 1987

Amplitude and Spectral Characteristics of Low Grazing Angle Acoustic Backscatter

A Paper Presented at the 112th Meeting of the Acoustical Society of America, 8-12 December 1986, Anaheim, California

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PREFACE

This document describes work performed under NUSC Project D20021, "Surface Ship ASW Advanced Development," Principal Investigator, Paul D. Koenigs; sponsored by Naval Sea Systems Command, Code 63D, CDR E. Graham, Program Manager; Program Element No. 63553N; Subproject No. S1704.

REVIEWED AND APPROVED: 17 February 1987

Larry Freeman

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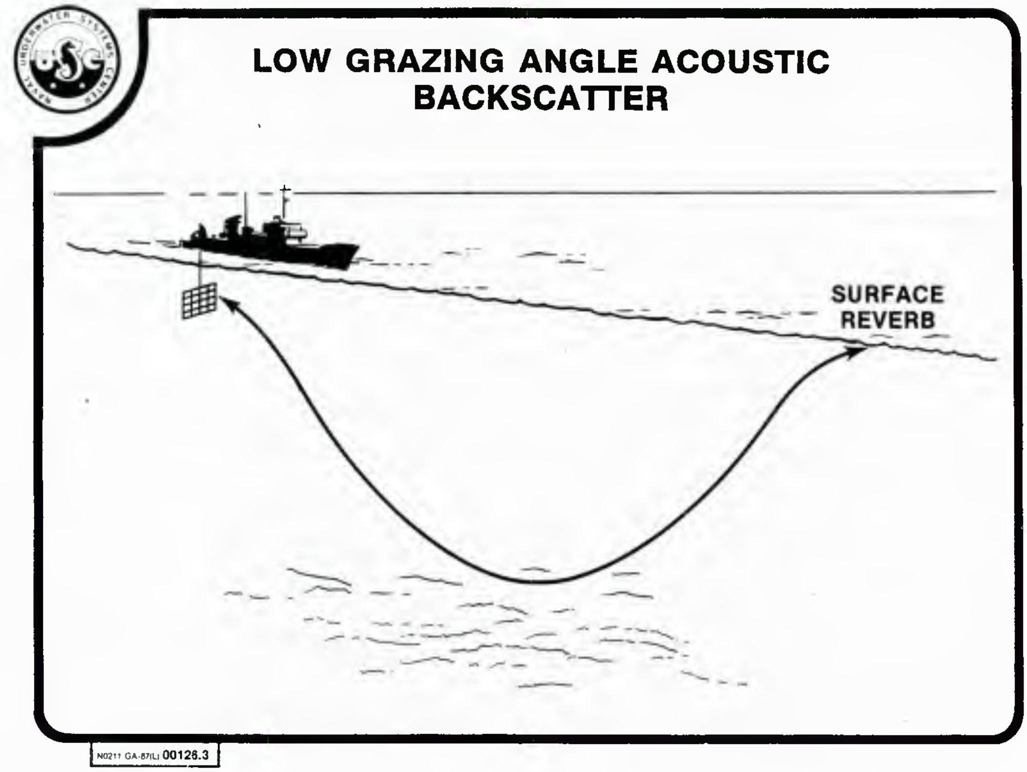
AMPLITUDE AND SPECTRAL CHARACTERISTICS OF
LOW GRAZING ANGLE ACOUSTIC BACKSCATTER



Viewgraph 1

There have been numerous theoretical and experimental investigations of acoustic backscattering from the sea surface as functions of grazing angle, roughness, wind speed, frequency, and the like. The current experimental data set in this respect is relatively restrictive, yet unique as it spans a narrow frequency band from 850 to 1350 Hz and a small set of grazing angles in the 5 degree range. The experiments were conducted in an area about 300 nmi southwest of Bermuda that has an average water depth of 5200 m. The transmit array was a 1.5 x 3 m planar array with an acoustic baffle on one side. To alleviate ship generated noise problems a special receiving array was constructed. This array consisted of two vertical line arrays summed as dipoles. This arrangement provided cancellation of ship-generated noise yet provided some array gain. The system was constructed and deployed from a drifting ship such that the maximum receiving response was closely aligned with the transmitter. The transmit system was energized using 10-second single-frequency pulses. The surface reverberation of interest arose from scattering sites located in the convergence zone at a range of 65 km, or about 80 seconds after each transmission. During the measurement period the oceanic and meteorologic conditions changed very little. The ship, hence, the transmitter orientation, was also quite stable so that all transmissions were in a down wind/down wave direction.

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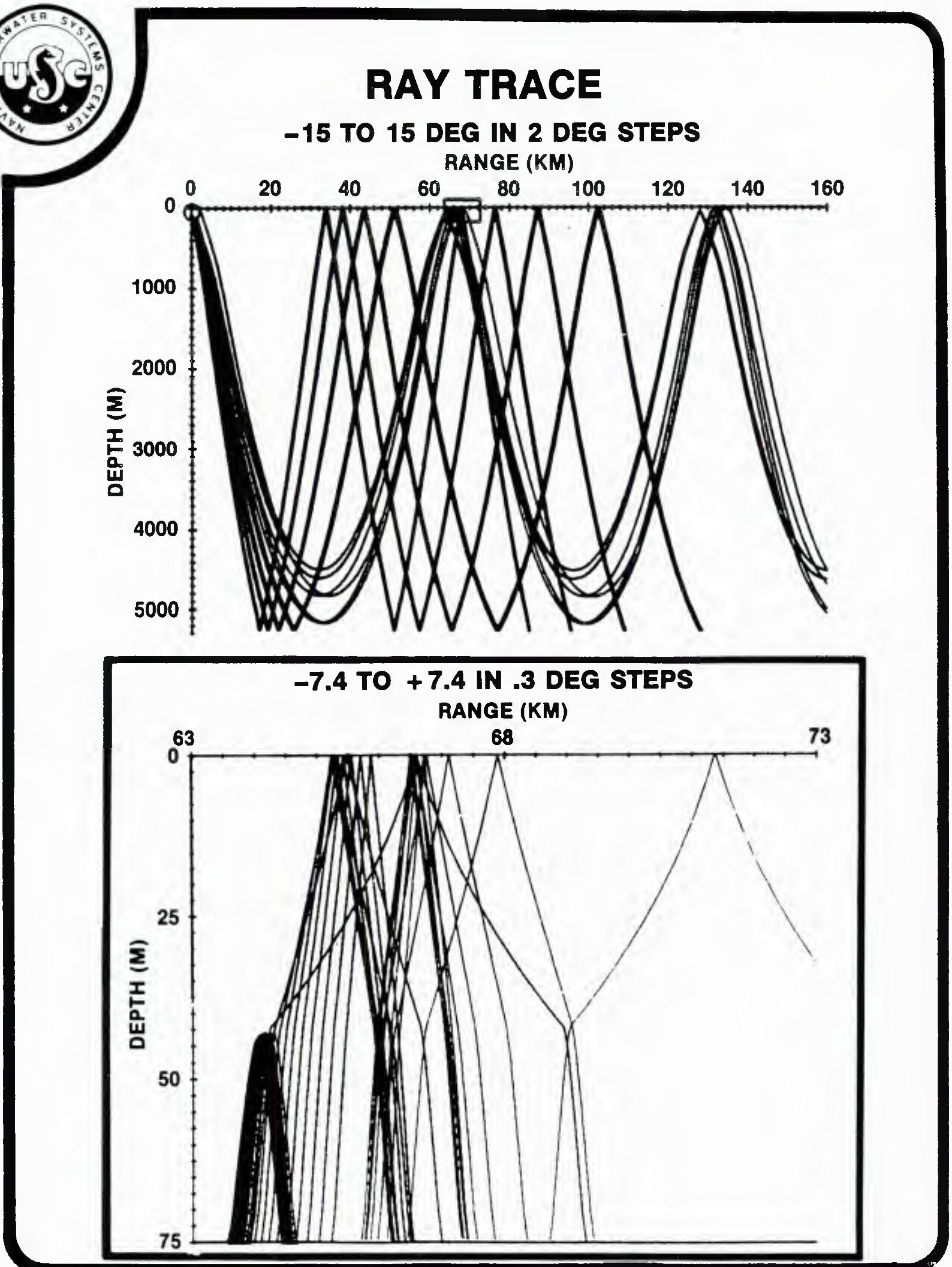

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Viewgraph 2

A sample ray trace using the average measured sound speed profile and a source depth of 45 m is shown in this viewgraph. The rays in the upper picture approximate the vertical beamwidth of the transmitter at 1 kHz when the steering angle is zero degrees. We can see in this case that the sea surface near 65 km can receive relatively high sound pressure levels. An expanded view of the rays approaching the sea surface near 65 km are shown in the lower figure. For this experimental geometry and speed profile we note the rays with source angles between plus and minus 4.4 degrees vertex near 42 m and do not reach the surface. Those rays with launch angle magnitudes between 7.4 and 4.7 interact with the surface at an average grazing of about 6 degrees. This interaction results in surface reverberation originating from a set of low grazing angles in the convergence zone.

-- Next viewgraph, please.

THEORY

$$I_{s_i} = \frac{I_{T_i}\,\alpha_i\,A_i}{(TLC_i)^2} \qquad (1)$$

$$L_R = L_I + S_b + 10\log ATL \qquad (2)$$

$$\text{WHERE} \quad ATL = \frac{\phi\pi}{360}\sum_i \frac{r_{i+1}^2 - r_i^2}{(TLC_i)^2}$$

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Viewgraph 3

The intensity of a backscattered acoustic wave is equal to the incident intensity times a scattering strength coefficient normalized to a unit area. The incident intensity is equal to the intensity of the transmitted wave times the transmission loss. When the transmitter and receiver are collocated the intensity of the backscattered wave is also reduced by the transmission loss. Thus, the intensity of a backscattered wave from an elemental unit scatterer may be defined by the uppermost equation. The S and T subscripts indicate scattered and transmitted, respectively, and α_i is the scattering strength coefficient per unit area, A_i is the unit area, and TLC_i is the transmission loss coefficient to the unit area. Thus, the total reverberation can be represented as a single sum or integration over the contributing scattering elements. The contributing extent or number of scattering elements may be determined by realizing that the reverberation at any instant of time is a convolution of the spatial impulse response of the scattering surface and the transmitted signal. When the pulse length is longer than the temporal extent of the surface impulse response, all elemental scattering sites contribute to the reverberation and a steady state or constant level is observed. Such is the case for 10-second transmission to an Atlantic convergence zone. Because the vertical beamwidth of the transmitter is relatively broad compared to source angles interacting with the surface, we may assume the transmitted intensity to each scattering site is constant. We may also assume the scattering coefficient from all contributing elements is relatively constant in the convergence zone because of the small range in grazing angles. In the convergence zone, the transmission loss varies substantially over the contributing scattering sites and the integration must be performed. For this case, equation (1) may be simplified to equation (2) where ϕ represents the horizontal beamwidth of the system. Estimates of TLC to each range were obtained using the Generic Sonar Model. Equation (2) may now be used to obtain backscatter strength, denoted here by S_b.

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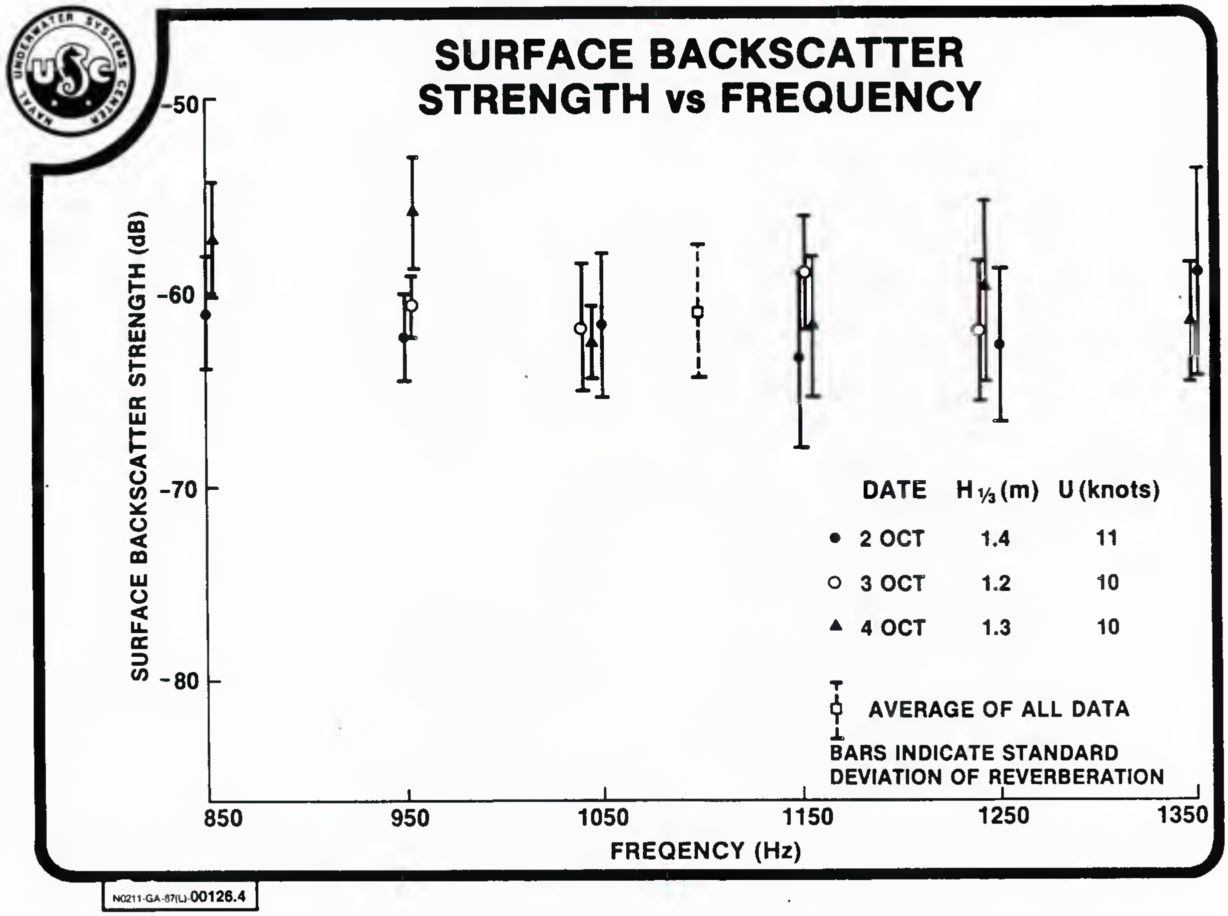

Viewgraph 4

Backscatter strengths for each data set obtained during the experiment are presented in this viewgraph. Each data point is an ensemble of the results from 8 to 12 transmissions and the bars indicate the standard deviation of the reverberation levels. Also indicated on the viewgraph are the measured average values of the significant wave height and wind speed during the data collection periods. It is apparent from the viewgraph that there is no significant dependence on frequency. The average backscattering strength for all the data is about -61 dB. To a first approximation this value agrees reasonably well with the prediction of the Chapman-Harris model. We should note, however, that the model is very sensitive to wind speed and grazing angle at these experimental values.

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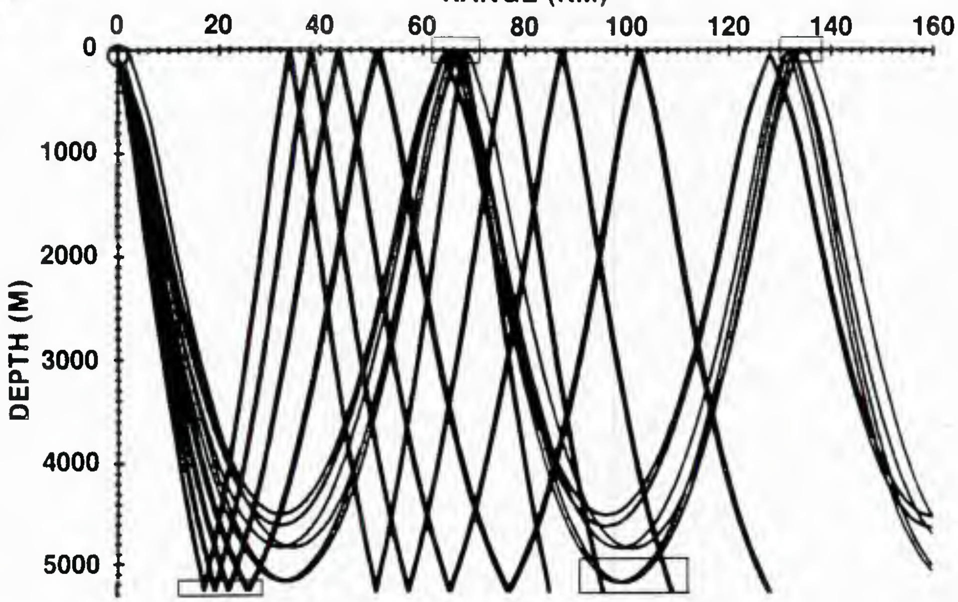
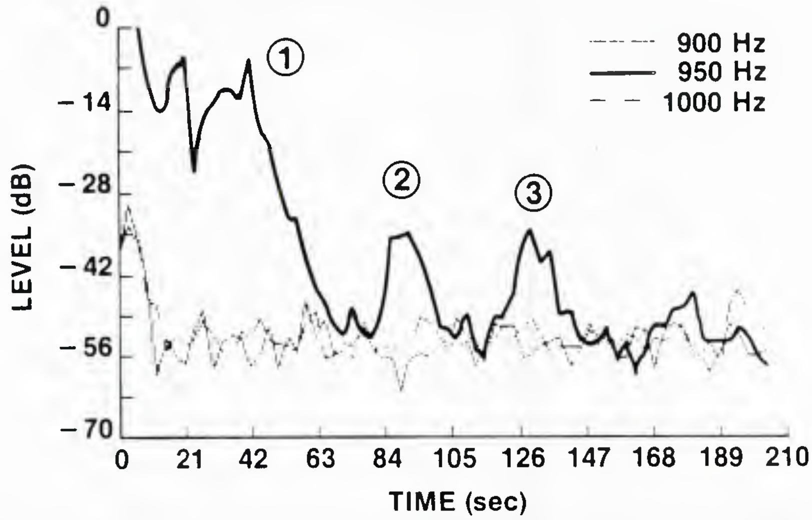
RAY TRACE

–15 TO 15 DEG IN 2 DEG STEPS



REVERBERATION vs TIME

- BOTTOM REVERB (1)
- SURFACE REVERB (2)
- BOTTOM REVERB (3)



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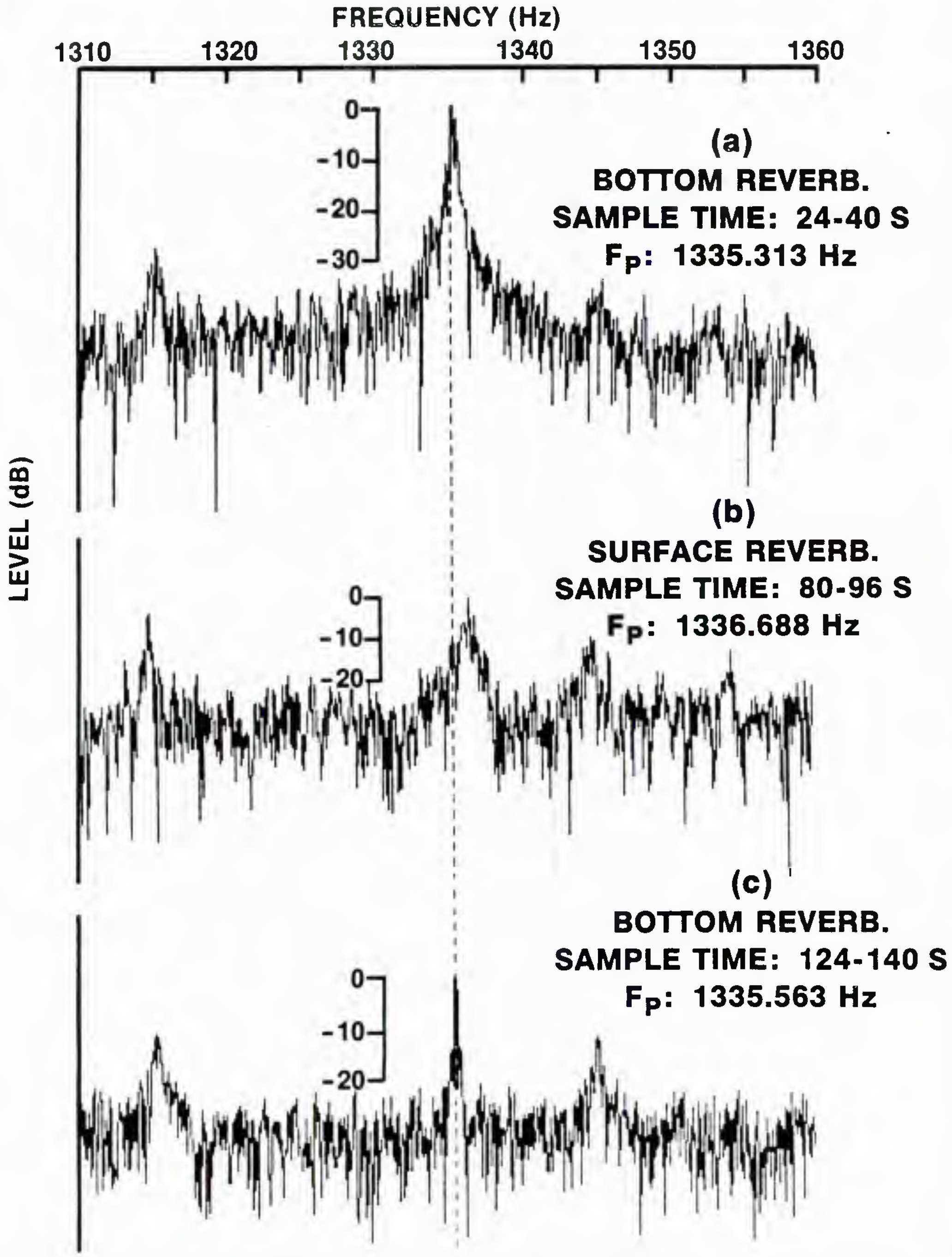
Viewgraph 5

The upper figure in this viewgraph is a ray trace based on the existing experimental conditions as shown earlier. Significant boundary reverberation might be expected from those areas indicated by the rectangles near 20, 65, 100, and, perhaps, 130 km. An example of the reverberation and noise in a 2.5 Hz band versus time from pulses at 950 Hz is shown in the lower figure. The high levels in the region marked by 1 are the result of bottom backscatter from direct path insonification. Region 2 levels are the result of surface interactions, and region 3 are the result of bottom interactions. The relatively constant levels at about -56 dB indicate the noise level in similar bandwidths centered at 900 and 1000 Hz. These provide an indication of the observed reverberation-to-noise level. To examine the spectral behavior of reverberation, single 16-second time records from the three different reverberation regions were transformed to the frequency domain.

-- Next viewgraph, please. --

SPECTRA OF BACKSCATTER ENERGY
PULSE LENGTH: 10 SEC
SPECTRAL RESOLUTION: 0.0625 Hz
REPLICA F_{PEAK} = 1335.313 Hz



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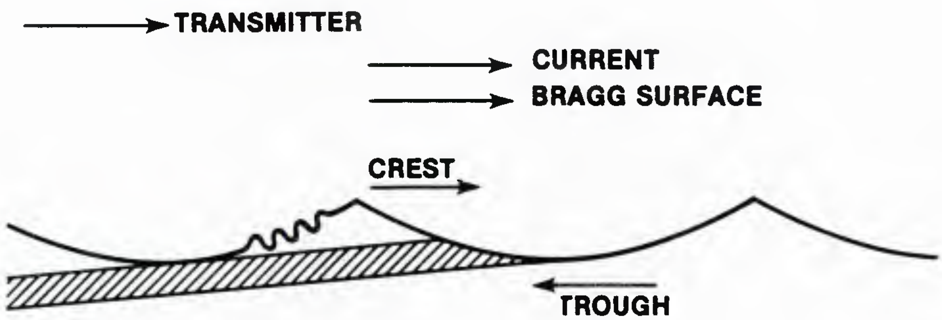
Viewgraph 6

The results of the transformation from a single transmission are shown in this viewgraph. The transmit frequency is 1335.313 Hz and the spectral resolution is 62.5 mHz. The spectrum of direct path bottom reverberation is shown in the upper figure. The power near 1335 Hz is from bottom reverberation. Other small peaks in power, for example near 1315 and 1345 Hz, are ship radiated tonals. In this case, the bandwidth of the signal is related to the large number of spatially distributed scattering sites. The spectra observed at 124 to 140 seconds, as seen in the lower figure, are the result of scattering from a very narrow range of grazing angles and relatively small 30 degree azimuthal sector. The maximum frequency shift corresponds to a ship drift speed of 0.3 knots or 0.15 m/s. The spectrum of reverberation generated at the convergence zone from a single pulse is shown in the center. Because the surface scatterers are in motion, it is not surprising the bottom and surface spectra are vastly different. Of particular interest at this point is the up-Doppler shift in the surface reverberation generated by transmissions in a down-wind direction.

-- Next viewgraph, please. --

DOPPLER VELOCITY COMPONENTS

$$f_D = \frac{2}{\lambda}\left[\vec{V_C} + \vec{V_B} + \vec{V_O} - \vec{V_T}\right]$$



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Viewgraph 7

Bass and Fuks, among others, have established that the spectrum width and shift of scattered electromagnetic energy from the sea surface depends on surface roughness and the angle between the direction of transmission and sea waves. Subsequent investigations have shown we must include other pertinent causes of relative motion between the transmitter and scattering surface. If we consider a differential area as a scatter site and a collocated transmitter and receiver, there will be a spectra shift in the received signals related to their velocities by the Doppler equation for small Mach numbers shown here. Lambda (λ) is the acoustic wavelength. V_T is the transmitter velocity. V_C is the mean drift current velocity. V_B is the velocity of the Bragg scattering surface indicated here by the small waves superimposed on the large waves. V_O is the orbital particle velocity resulting from the large ocean wave propagation. A positive value is associated with a particle at a wave crest and a negative value at a wave trough. At low grazing angles when acoustic shadowing becomes important, preferential insonification of the wave trough occurs. When the site and transmitter net velocities are deterministic, we observe a simple Doppler shift in the received spectra. If a scatter site's velocity and/or the velocity of all contributing sites is random, a widening of the spectrum occurs. We can, therefore, consider spectrum spread as a special case of Doppler shift.

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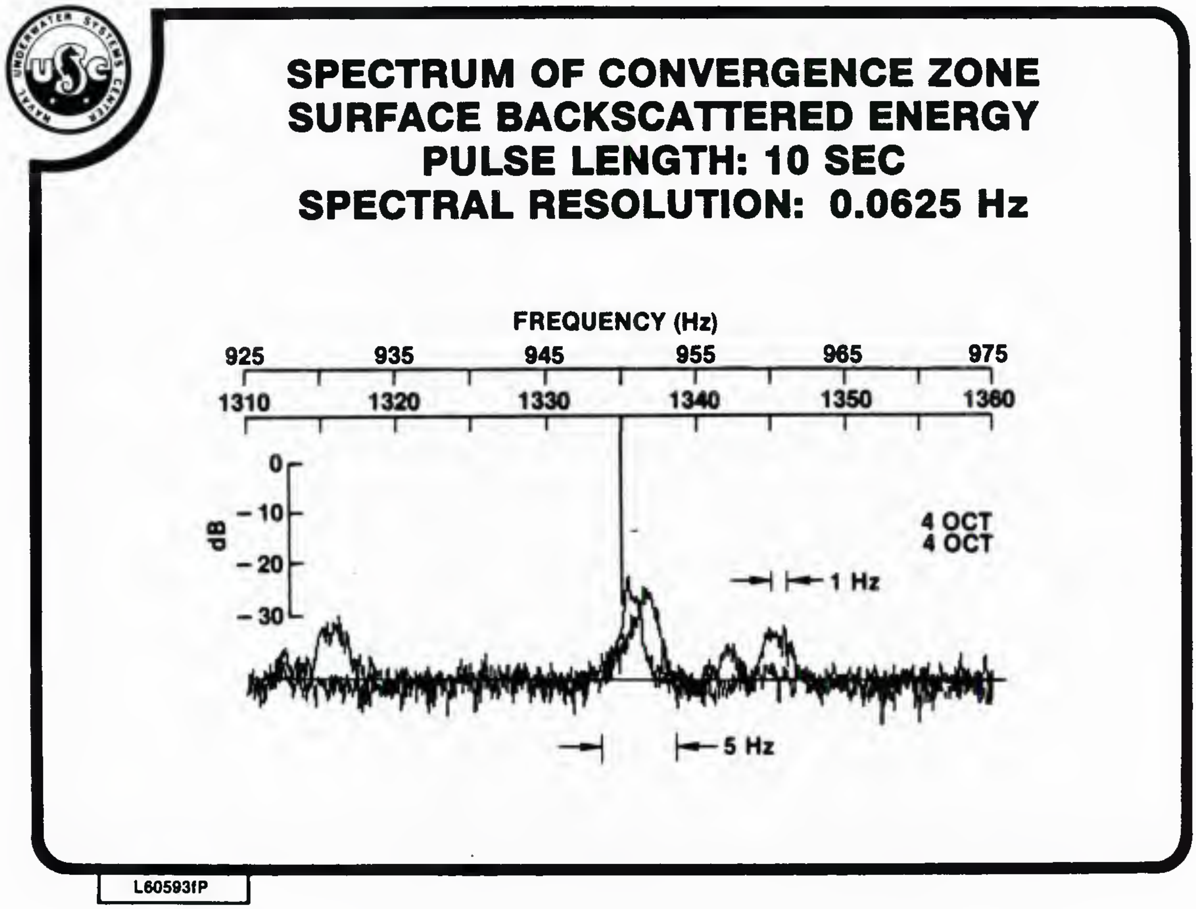
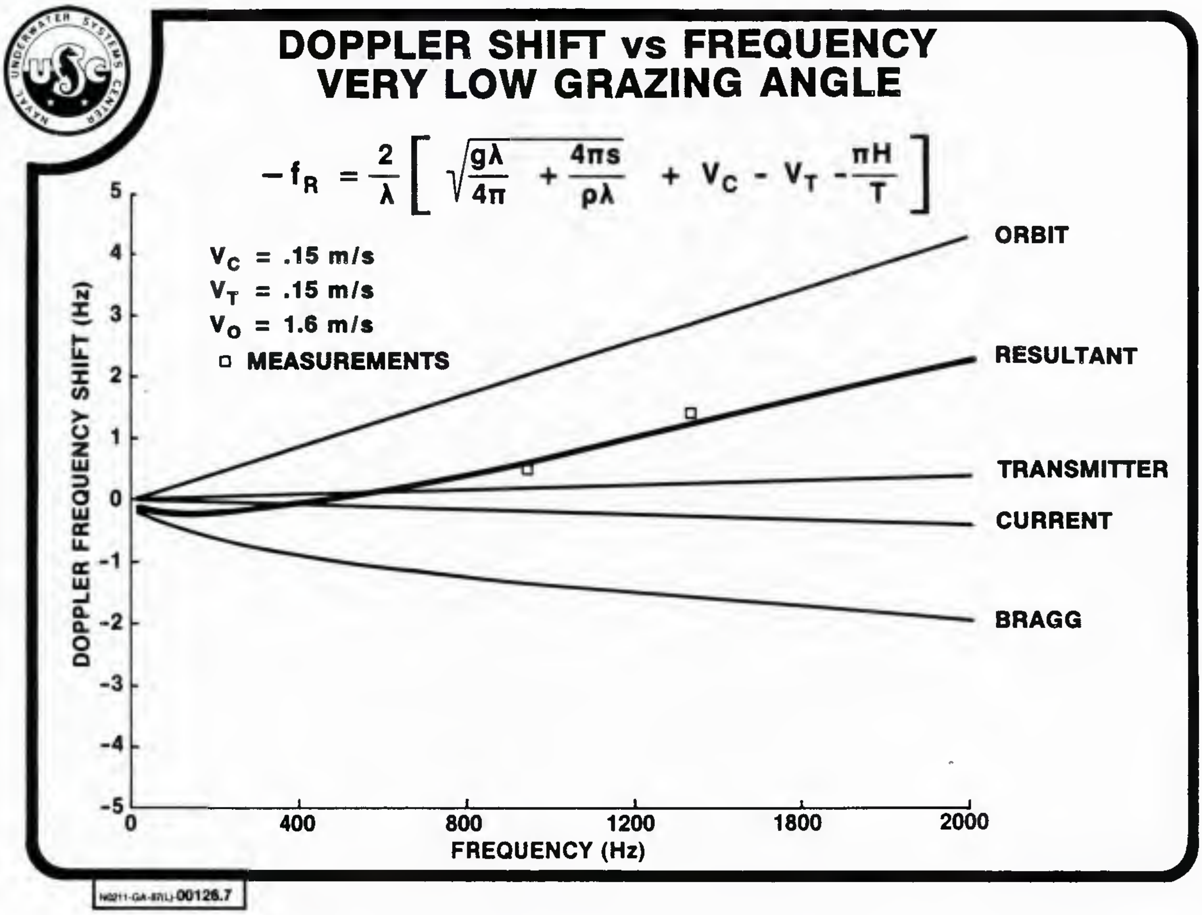


Viewgraph 8

To reduce measurement variance and obtain better spectral estimates, the spectrum from eight consecutive pings were used to produce average spectral estimates. The average estimates obtained on 4 October near 1335 and 950 Hz are depicted in this viewgraph. We see the spectral spread and frequency of maximum power near 1335 Hz are greater than at 950 Hz as expected. Also note that the Doppler shifts are positive. This indicates a closing range rate between the transmitter and scatter sites. For the case of a drifting ship and transmissions in a down-wind, down-wave direction, this can only occur when wave troughs are preferentially insonified. As mentioned earlier, the peaks in power at frequencies somewhat removed from the transmit signal are ship radiated tonals.

-- Next viewgraph, please. --

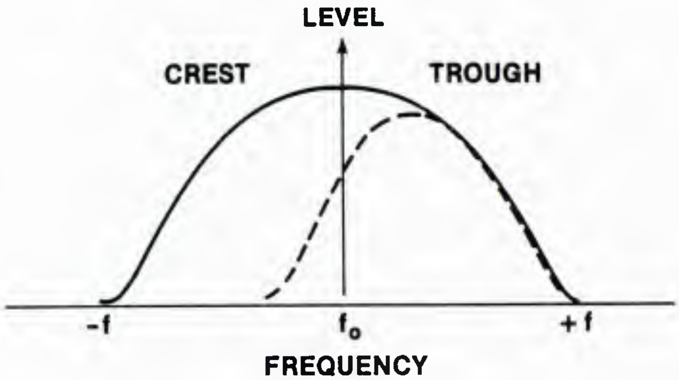


Viewgraph 9

Some insight into the frequency dependence of Doppler shifts arising from low grazing angle acoustic backscatter at the sea surface can be gained by evaluating the equation at the top of the figure using experimental data. Because the ship was drifting with the current, V_C and V_T cancel. The resultant frequency shift is merely the result of a down- Doppler caused by the Bragg scattering surface moving away from the transmitter with a speed given by the first term in the brackets, and an up-Doppler shift caused by the surface layer in the wave trough moving toward the receiver with a speed given by the last term in brackets. For comparison, the measured Doppler shifts at 950 and 1335 Hz are shown on the viewgraph. If preferential insonification of the wave troughs were not occurring, Bragg scattering would be the only mechanism shifting the frequency of the signal. This would result in a down-Doppler shift, which was not observed in the experimental data.

-- Next viewgraph, please. --

SURFACE REVERBERATION SPECTRUM



$$\Delta f = \frac{2}{\lambda} \bullet \frac{\pi H}{T} \cos(Kx - \alpha t)$$

ACOUSTIC OCEANIC

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Viewgraph 10

The total range of Doppler shifts arising from insonification of one deep water ocean wave may be expressed by the equation shown in this viewgraph. As before, the first term is related to the transmitted acoustic wavelength and the second term to orbital particle velocities. Where H is the wave height, T the wave period, K the wavenumber, and α the radian wave frequency. Evaluating this equation over one wave length can result in a range of orbital speeds from $\pi H/T$ to $-\pi H/T$. The negative value is associated with a particle at a wave peak traveling in the wave direction and the positive value associated with a particle at the wave trough traveling opposite to the wave direction. When there is a continuum of wave heights and periods, spectra as indicated by the solid line in the viewgraph are observed. For very low grazing angles, the entire wavelength is not insonified and the spectral width of the scattered energy will be somewhat diminished as indicated by the dashed line in the viewgraph.

-- Next viewgraph, please. --

SURFACE REVERBERATION BANDWIDTH VERY LOW GRAZING ANGLE

f_o (Hz)	MEASURED (Hz) −10 dB	PREDICTED (Hz) *
950	2.0 ± .5	2.1
1335	2.4 ± .5	2.9

* PREFERENTIAL INSONIFICATION OF WAVE TROUGH

$$\Delta f = \frac{2\pi H_{1/3}}{\lambda T_l}$$

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Viewgraph 11

Shown here is a comparison between measured and predicted spectral bandwidths. For the comparison, I have arbitrarily selected a measurement bandwidth at -10 dB. It appears an unorthodox combination of significant wave height and the lowest wave period yield predictions close to the measured values. At this time it is not clear which combination of wave heights and periods should be used. It is clear that, under these experimental conditions, the spectral bandwidth is notably smaller than predicted if the effect of shadowing is neglected.

-- Next viewgraph, please. --

CONCLUSIONS

VERY LOW GRAZING ANGLE ACOUSTIC BACKSCATTER

- MEASURED BACKSCATTER STRENGTH AT LOW WIND SPEED AGREES REASONABLY WELL WITH CHAPMAN-HARRIS
- ACOUSTIC SHADOWING OF THE SURFACE IS APPARENT
- DOPPLER SHIFT IS DEPENDENT ON THE BRAGG SCATTERING COMPONENTS AND THE SIGNIFICANT OCEAN WAVES
- SPECTRAL SPREAD OF BACKSCATTERED ENERGY IS SOMEWHAT DIMINISHED BY PREFERENTIAL WAVE TROUGH INSONIFICATION

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Viewgraph 12

In conclusion, the average backscattering strength in the 1 kHz regime at low grazing angles and low wind speeds appears to be frequency independent and agrees reasonably well with the Chapman-Harris model.

The spectrum of low grazing angle surface backscatter is affected by shadowing. Under these conditions, the conventional equations for Doppler shift and spectral spread should not be separated. The frequency shift of surface backscatter is dependent on the environment through the velocity of the Bragg surface, mean drift currents, and orbital particle motion. The Bragg surface velocity is dependent on small ocean waves and particle motion is dependent on large ocean wave height and period.

The spectral spread of surface backscattered energy is still dependent on particle velocity but somewhat diminished because wave troughs are preferentially insonified.

Thank you, are there any questions?

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